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13. ABSTRACT (Maximum 200 words)  The two complex elastic moduli (and the corresponding shear and longitudinal sound speeds) of a voided polymer have been measured as a function of frequency between 0.5 and 2.5 kHz by laser Doppler interferometry and finite element modeling. The measurement errors associated with this new technique are discussed.				
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# **ANNUAL LETTER REPORT**

## **11/12/97**

### **ONR Grant Information**

Grant Title:	Laser Measurements of Elastic Moduli of Voided Polymers
Performing Organization:	Georgia Institute of Technology
Principal Investigator:	Yves H. Berthelot
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ONR Scientific Officer:	Geoffrey L. Main

## **Laser Measurements of Elastic Moduli of Voided Polymers**

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### **Research Objectives**

To determine experimentally the two complex elastic moduli (bulk and shear) of a voided polymer within known and acceptable error bounds.

### **Methodology**

- To develop the laser-based (LDV) / finite element (FEM) technique.
- To validate the technique / Quantify the error bounds.
- To extend the measurement technique to a controlled Temperature / Pressure chamber.

### **Technical Approach**

A sample of arbitrary shape (typically, a rectangular block of 1"x2"x3") is excited harmonically at its base (by a shaker or a piezoelectric stack). The surface dynamics of the sample is non-invasively measured at several points (in-plane and out-of plane surface velocities - amplitude and phase) by a set of four independent fiberoptic laser Doppler interferometers and referenced (amplitude and phase) to its base motion. The material parameters are determined from a least-square fit between the experimental data and numerical predictions obtained from a finite element code in which the frequency-dependent elastic moduli are the adjustable parameters.

### **Recent Accomplishments**

#### **1. Major results**

- *Measured the frequency-dependent, complex sound speeds (shear and longitudinal) simultaneously in the same sample in the 0.5 - 2.5 kHz range. (The frequency range could be lowered with a larger sample).*  
*results:* see Figure 1 (solid line). Note that the vertical scale is greatly expanded around the mean value, thus indicating the remarkable precision of the technique.
- *Intrinsic variability (repeatability): Performed a statistical analysis of the data, over 64 sets of data, to measure the variance of the data obtained with the same sample and the same measurement apparatus. Estimated the resulting variance of the complex sound speeds.*  
*results:* see Figure 1 (dashed lines). The dashed lines correspond to the sound speeds evaluated with the mean surface velocities  $\pm 1$  standard deviation. This

shows that the error in amplitudes and phases of the measured surface velocities translate into variation of sound speeds less than 1%.

Relative error (*) (1.0-2.5 kHz)	real part	imaginary
Longitudinal sound speed	<1% (1%)	<1% (3%)
Shear sound speed	<1% (1%)	<1% (3%)

(\*) values indicate the typical average error over the frequency range. Values in parentheses indicate the maximum error in that frequency range.

- True variability between measurements (**same sample**): Tested the effect of the variability of bonding the sample to the base, i.e., repeated the measurements with the *same* sample, *before debonding and after rebonding* to the same base. In each case, the base was excited with a different drive: a Ling shaker and a piezoelectric stack. The relative errors measured with the same sample tested with the two drives (and with debonding and rebonding to the base) are shown in the table below.

Relative error (*) (1.0-2.5 kHz)	real part	imaginary
Longitudinal sound speed	3% (4%)	10% (13%)
Shear sound speed	3% (4%)	12% (20%)

(\*) values indicate the typical average error over the frequency range. Values in parentheses indicate the maximum error in that frequency range.

- True variability between measurements (**different samples**): Tested the method with *two samples* taken from the *same* piece of material, both with the same excitation (Ling shaker).

Relative error (*) (1.0-2.5 kHz)	real part	imaginary
Longitudinal sound speed	4% (5%)	10% (16%)
Shear sound speed	4% (5%)	10% (16%)

(\*) values indicate the typical average error over the frequency range. Values in parentheses indicate the maximum error in that frequency range.

- *Compared the results* with independent (in-situ) measurements made by Jarzynski et al. on a large chunk of the same material. Also, compared the results with Kerner's model in which the matrix material properties were calculated using experimental data obtained with the DMTA apparatus (results provided by Walt Madigosky).

results: (a) In situ results: Sound speeds are in reasonable agreement with our measurements, but at present, the in-situ results are only accurate within 10 to 20% and only the real part of sound speeds has been estimated.

(b) Kerner's model. The comparison with Kerner's simple model of voided polymers is not really meaningful because we don't know the material properties

of the host material. (We had to estimate the properties from measurements made with the DMTA, measurements provided by W. Madigosky). Nevertheless, the comparison between measured values of sound speeds and predicted values was remarkably close.

- Designed and started to build an-improved, compact, 2 probe, scanning LDV system to make similar measurements inside a *temperature/pressure controlled chamber*. (Temperature range: 40F-100F, pressure 0 - 500 psig).

## 2. Other results

- Measured the *spatial uniformity of the base motion* (0.5 to 3 kHz). Compared the uniformity of several bases (including a wedge), and excitation by the Ling shaker, the B&K 4810 shaker, and several piezoelectric stacks.

*result:* The piezoelectric stack (Sensor Technology) performs best. A simple aluminum base to support the sample works best.

- Tested for the *best combination of bondings* between the piezoelectric stack, the back mass, the base, and the sample.

*result:* best results were obtained with the piezoelectric stack bonded to a massive lead brick using uncured butyl rubber; the aluminum base supporting the sample was attached to the stack with rubber cement; and the sample was super-glued to the base. With this arrangement, the nonuniformity of the base motion was less than 2% below 2 kHz and less than 4% at 3 kHz. (Results with the Ling shaker were worse.)

- Assessed the effects of using small reflective tapes or small spots of white paint on the sample, for either in-plane or out-of-plane measurements.

*results:* the effect appears negligible.

- *Sensitivity analysis on the position of each laser probe:* Performed numerical experiments (with measured data) to assess the relative contributions of the measurements made by each laser probe on the resulting material properties.

- *Sensitivity analysis of the numerical code:* Performed numerical experiments to test the dependence of the results on (a) the initial guesses of material properties (Young's modulus, loss factor, and Poisson ratio); and (b) the mesh size in the finite element code.

*results:* the material properties are independent of the initial guesses. They remain also identical if the mesh size is increased, thus indicating that the method is very robust and does not converge towards false minima.

## **Future Plans**

- Test the measurement method with samples of known properties: (a) lucite; (b) "round robin" sample to be provided by J.Dlubac / G. Szilagy. (NSWC-Carderock).

- Expend on the error analysis:
  - effect of a 1% error in the sample height on inversion procedure
  - effect of a small error in the positioning of the laser probe
  - effect of a 1% error in the density of the sample.
- Assess whether it is feasible / desirable to replace the current in-house FEM Fortran code with the FEM Matlab toolbox.
- Complete the design of the experimental setup for the pressure / temperature chamber, and perform preliminary tests. Compare results with DMTA apparatus, Trivett's bulk modulus measurements, etc...

## Relevance to the Navy

Effective ship hull treatment depends in part on a good understanding of the acoustic properties of the viscoelastic layer attached to the hull. Measuring the shear and bulk dynamic moduli of a viscoelastic sample is therefore critical to predict correctly acoustic performance. Two of the most common experimental techniques used to measure dynamic moduli are the resonant technique (Madigosky and Lee) and the DMTA (Dynamic mechanical testing apparatus), both of which are very useful but have some intrinsic limitations. A new technique developed by Trivett a NUWC is also very promising but it can measure only one elastic modulus (bulk modulus). The proposed laser-based experimental/numerical technique is an alternative, noncontact, method capable of measuring *simultaneously both shear and bulk moduli.*, an important advantage since manufacturing variabilities and hysteretic material response are common sources of errors.

## Publications (1996-1997)

### 1. Relevant to this Grant

R. L. Willis, T. S. Stone, Y. H. Berthelot, and W. Madigosky, "An experimental-numerical technique for evaluating the bulk and shear dynamic moduli of viscoelastic materials," to appear in J. Acoust. Soc. Am., **102** (5), Pt 1., (1997)

T. S. Stone, "A numerical-experimental method for evaluating the bulk and shear complex dynamic moduli of viscoelastic polymers in the kilohertz range," M.S. thesis, Georgia Institute of Technology, September 1997.

S. H. F. Lin, "A laser interferometer for measurement of surface vibrations and ultrasound", M.S. thesis, Georgia Institute of Technology, September 1997.

A. C. Moore, "An improved system for measuring optically the surface dynamics of a sample", M.S. thesis, Georgia Institute of Technology, September 1997.

R. L. Willis, T. S. Stone, Y. H. Berthelot, "A laser-based experimental-numerical technique for evaluating the bulk and shear dynamic moduli of viscoelastic moduli," J. Acoust. Soc. Am. 101 (5), part 2, (1997); presented at the ASA meeting, Penn State University.

### 2. Other publications

J. P. Chambers, and Y. H. Berthelot, "An experimental investigation of the propagation of sound over a curved, rough, rigid surface," J. Acoust. Soc. Am. 102 (2), Pt 1, 707-714 (1997)

Y. H. Berthelot and J. P. Chambers, "On the analogy between sound propagation over a rough surface and sound propagation over a smooth surface with modified surface impedance," Proceedings of the 7th Long Range Sound Propagation Symposium, Lyon, France, 1996.

Y. H. Berthelot, "A note on the acoustic penumbra behind a curved surface," J. Acoust. Soc. Am., 99, 2428-2429 (1996).

J. P. Chambers, R. Raspet, Y. Berthelot, and M. White, "Use of the fast field program for predicting diffraction of sound by curved surfaces," J. Acoust. Soc. Am. 102 (1), 646-649 (1997)

M. A. Johnson, Y. H. Berthelot, P. Brodeur, and L. Jacobs "Investigation of laser generation of Lamb waves in copy paper," Ultrasonics, 34, 703-710 (1996)

M. A. Johnson and Y. H. Berthelot, "Antisymmetric nature of the lowest order fast Lamb mode for ultrasonic propagation in copy paper," J. Acoust. Soc. Am., Vol 101, 646-649 (1997)

M. Johnson and Y. Berthelot, "Laser ultrasonics in copy paper", Opt. Eng. Vol. 36, No. 2, 408-416, (1997).

J.-C. Cheng and Y. H. Berthelot, "Theory of laser-generated Lamb waves in orthotropic plates," J. Phys. D: applied Phys. 29(1), 1-11 (1996)

Z. Li and Y. Berthelot, "Crack detection in annular components by ultrasonic guided waves," Proceedings of QNDE'97, Quantitative Nondestructive Evaluation, Ed. D. Chimenti, Plenum, New York, pp. (1997).

### Frequency-dependence of the complex sound speeds

- solid line: sound speeds evaluated with the mean value of the surface velocities (64 acquisitions at each of the 5 surface points measured)
- dotted lines: sound speeds evaluated with the mean value  $\pm 1$  standard deviation of the surface velocities (64 acquisitions at each of the 5 surface points)

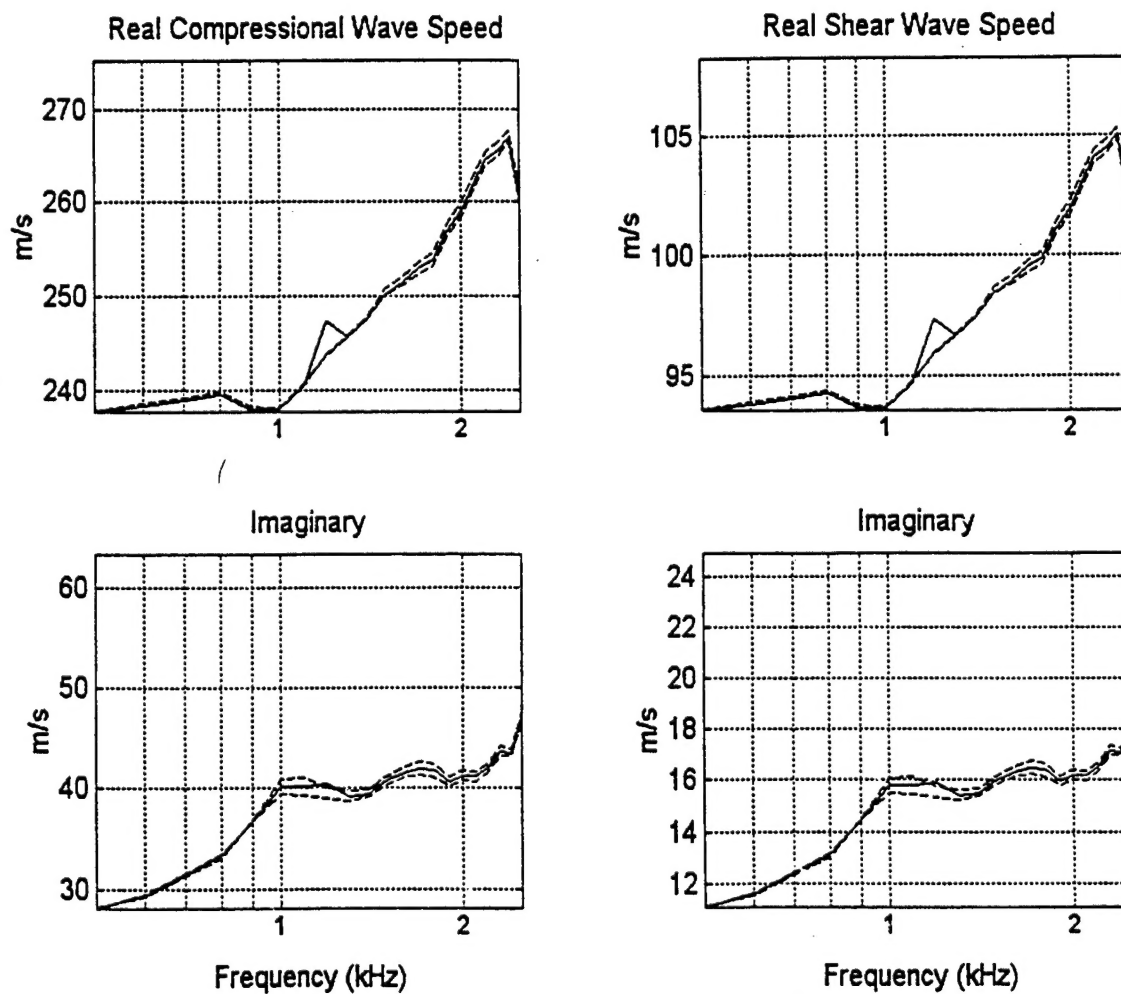


Figure 1

Variability between 2 samples from the same batch.

Frequency-dependence of the complex sound speeds

solid line: sample #1 - dashed line: sample #2

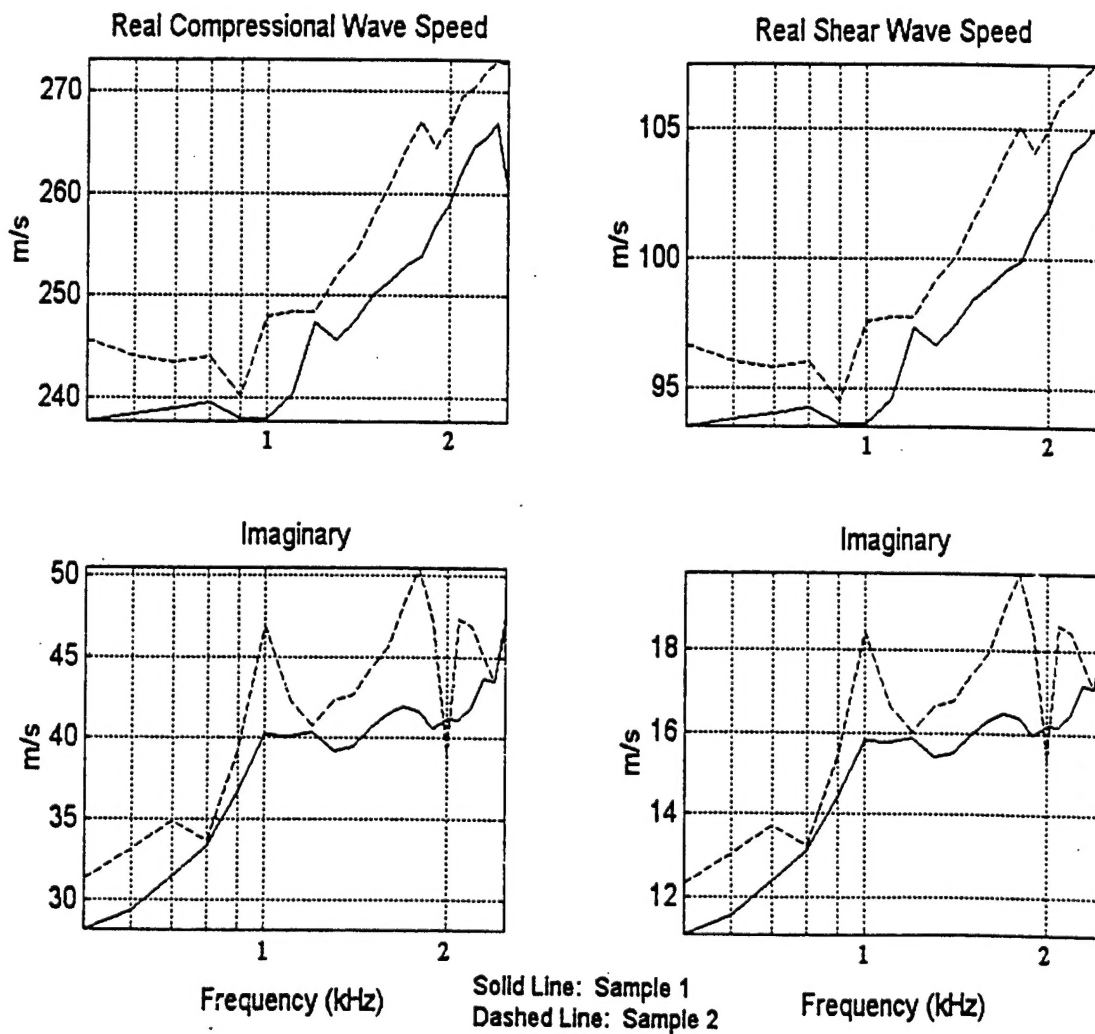


Figure 2